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Geomagnetic Response to Large-amplitude interplanetary Alfvén Wave Trains

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Abstract

A review of the geomagnetic response to large-amplitude interplanetary Alfvén-wave trains (LAIAWT) is presented, highlighting its dependence on solar activity level and its role in the storm/substorm relationship problem Also sonic recent observations obtained by the Ulysses spacecraft at high heliospheric latitudes dealing with the origin and dynamics of these wave trains arc discussed

1. Introduction

Large-amplitude Alfv&r-wave trains were observed in the interplanetary medium, within I AU, initially by Coleman [1] and by Becher and Davis [2]. These waves were found to exist typically in the trailing portion of high-speed streams. These authors also found that such wave trains propagate mainly outwards from the sun. Later on, Tsurutani and Gonzalez [3], using plasma and magnetic-field measurements obtained by the ISEE-3 satellite, in orbit around the inner Lagrangian point L_1 of the sun–earth system. demonstrated a close association between LAIAWTs and high-intensity, long duration, continuous auroral activity (HILDCAA) intervals. These authors showed that this type of auroral response occurs in association with LAIAWTs independent of geomagnetic storms or at times also during the recovery phase of the storm. However, such auroral activity is not part of the decay of the storm but is due to freshly injected solar wind energy.

Tsurutani and Gonzalez [3] also found that the LAIAWTS are often detected several days after major interplanetary events, such as shocks and solar wind density enhancements. Later on, Tsurutani et *al.* [4] showed that magnetic reconnection between the soothward components of the Alfvén-wave magnetic fields and magneospheric fields is the mechanism for energy transfer of solar wind energy to the magnetosphere.

In this review some aspects of the association between LAIAWTs and HILDCAAs are addressed, especially about its dependence on solar activity level and about its role in the storm/substorm relationship problem. Furthermore, some recent observations obtained by the Ulysses spacecraft related to LAIAWTs as well as some considerations about the origin of these waves will be also added in the Discussion section.

2. Dependence of LAIAWT/HILDCAA association on solar activity

2.1. *Solar maximum*

The measurements obtained by the ISEE-3 satellite (1978-1979) refer to the solar maximum interval, as discussed by Tsurutani and Gonzalez [3]. One example of a HILDCAA event during that interval is given in Fig. 1. The panels shown in

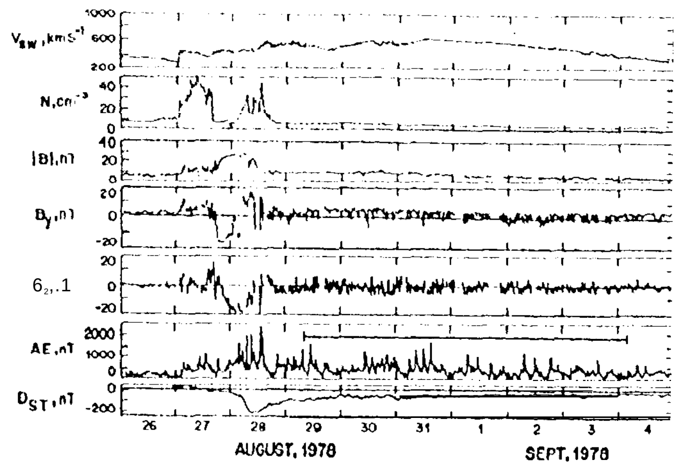

Fig. 1. Example of ISEE-3 observations, during solar maximum, of LAIAWTs and associated HILDCAA events (indicated by an horizontal bar in the AE panel).

this figure are, from top to bottom, solar wind speed, density, total interplanetary magnetic field (IMF) intensity, B_y and B_z components of the magnetic field (in solar ecliptic coordinates) auroral electrojet (substorm intensity) index AE and storm time (ring current) index D_{st}. The HILDCAA event is indicated by a horizontal bar in the AE panel covering the August 29–September 4 interval, The intense magnetic storm of August 28 was caused by a large southward B_z event on August 27–28. This and nine other similar intense storm intervals were studied by Gonzalez and Tsurutani [5], whereas seven other HILDCAA intervals, similar to that of Fig. 1, were reported by Tsurutani and Gonzalez [3]. All HILDCAA intervals were shown to be associated to LAIAWTs in the solar wind, as that shown by the panels B_y and B_z fluctuations for the HILDCAA event of Fig. 1.

10 determine if the mechanism for energy transfer from the solar wind to the magnetosphere is magnetic reconnection associated with the southward components of the Alfvén-waves, Tsurutani and Gonzalez [3] performed cross-correlation analyses between the IMF z-component and the AE index. For the majority of the events analyzed the correlation coefficients were anomalously low. The authors hypothesized that there could be several possible reasons for such a finding: (1) because ISE13-3 was often at the wings of the Male'' orbit (around the L_1 libration point) during the HILDCAA events, it is possible that the Alfvén-waves detected at ISEE-3 did not have the same phase and amplitude as impinged upon the magnetosphere: (2) a mechanism other than reconnection was the responsible

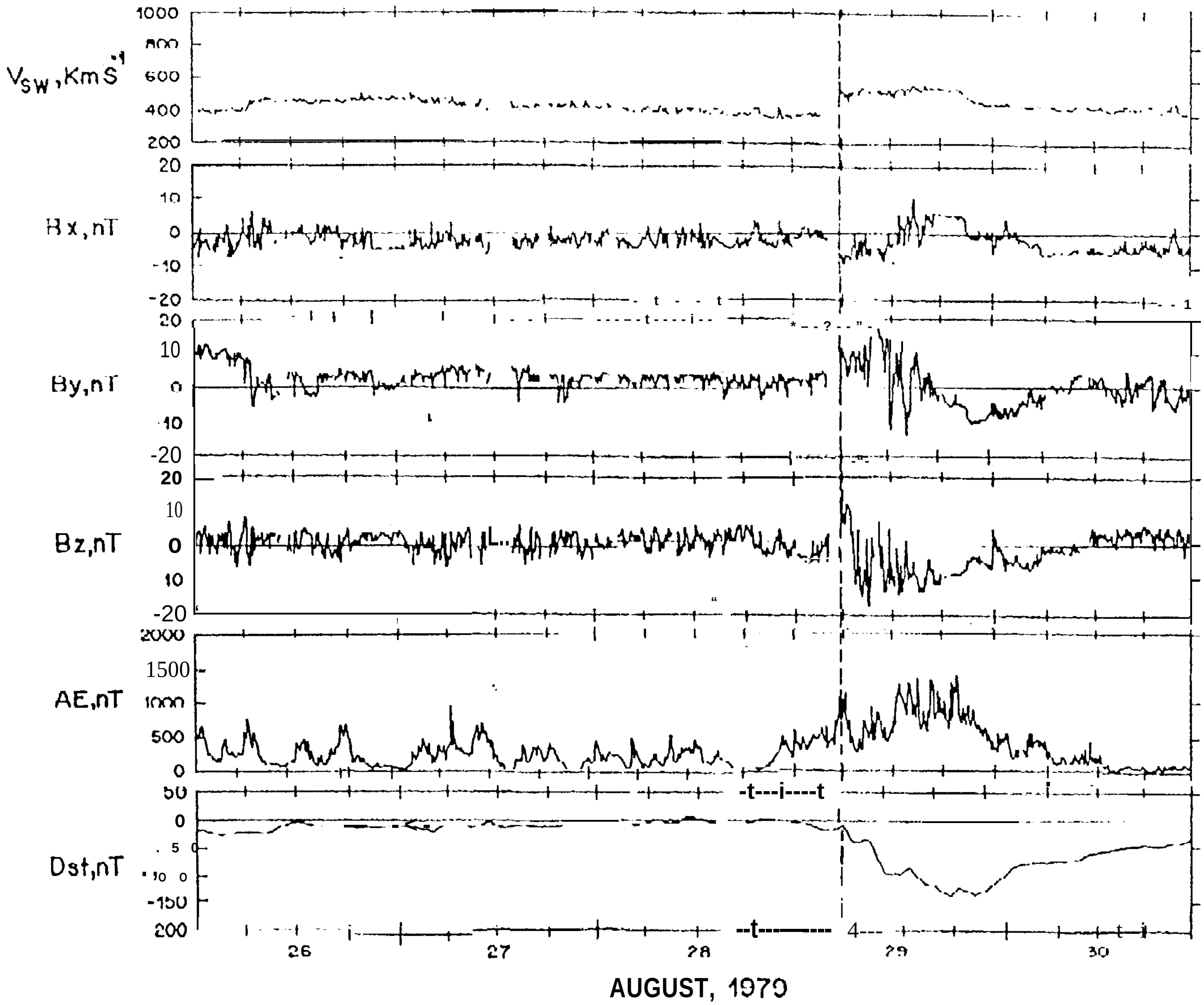

Fig. 2. Example of a LAIAWT interaction with an interplanetary shock, as observed by the ISEE-3 satellite.

mechanism; or (3) reconnection is the mechanism, but because the magnetosphere was in a highly turbulent state, auroral activity was not directly correlated to geomagnetic activity.

To answer this problem, Tsurutani *et al.* [4] examined interplanetary data from another satellite (IMP-8) which was located much closer to the magnetosphere, during the HILDCAA events of interest. Cross-correlation analyses similar to those performed with the ISEE-3 data were also performed with the IMP-8 data. The results showed a much stronger correlation between the southward component of the LAIAWTS and AE, indicating that magnetic reconnection is the responsible mechanism for the solar wind-magnetosphere energy transfer. Thus it is apparent that the lack of correlation between the ISEE-3 data and AE was due to the unfavorable location of the ISEE-3 spacecraft and the relatively small wavelengths of the Alfvén-waves.

Figure 2 shows an interval with LAIAWTs prior to an intense magnetic storm, which occurred on August 29. This interval is accompanied by a quasi-HILDCAA event, namely continuous auroral activity but of a smaller intensity than that defined for a HILDCAA event. Tsurutani and Gonzalez [3] used the following criteria to define a HILDCAA interval: (1) the substorm intensity, measured by AE, must reach a peak intensity greater than or equal to 1000 nT sometime during the event; (2) the event must have a duration of at least 2 days; (3) the auroral activity must be nearly continuous, namely, AE never drops below 200 nT for more than 2 hours at a time; and (4) the auroral activity occurs outside the main phase of a magnetic storm. Fig. 2 shows also the B_x component of the IMF, although the solar wind density and total IMF intensity are not shown in this case. The dashed vertical line around 06:00 hours of August 29 shows the arrival of an interplanetary shock and also the start of larger negative B_z fields which are responsible for the intense storm.

This is an example of a LAIAWT/shock interaction which seems to lead to more intense fluctuations in the IMF with negative B_z components large enough to produce an intense storm. At the moment the nature of the LAIAWT/shock interaction is not understood, but shock compression of the waves must clearly be present.

2.2. *Solar minimum*

Whereas LAIAWTs during solar maximum are associated with high-speed streams of the transient type the Alfvenic fluctuations during solar minimum are related to corotating

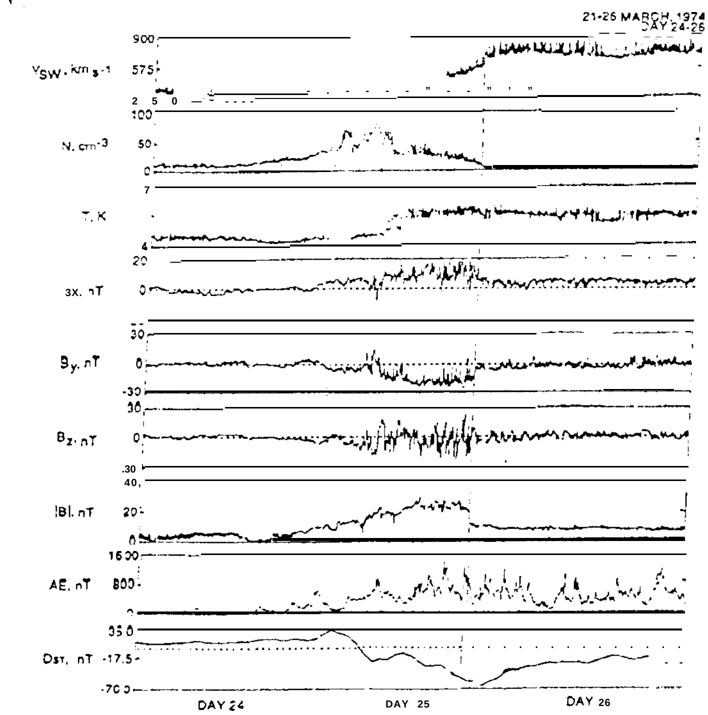

Fig. 3. Example of LAIAWT, HILDCAA and high-speed stream/heliospheric current sheet interaction during solar minimum, as observed by an IMP satellite.

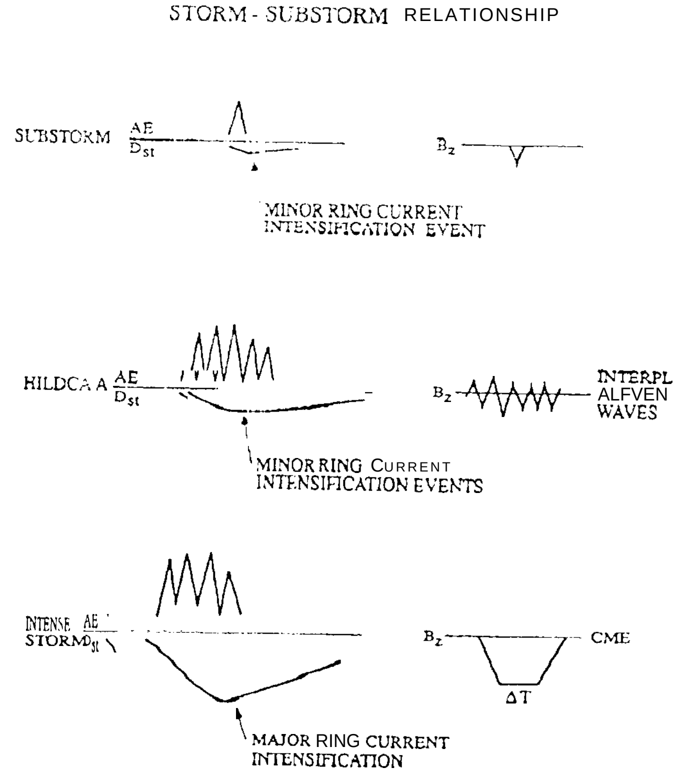

Fig. 4. Schematic showing a contrast between a typical substorm, a HILDCAA event and an intense storm event

streams, originated in recurring long-lived coronal holes at the sun. Fig. 3 is an example of a LAIAWT/HILDCAA association, related to a corotating stream during solar minimum, as measured by an IMP satellite. With reference to Figs 1 and 2, in this figure the plasma temperature is also shown (third panel). The corotating stream in this example extends from about the dashed vertical line onwards. This vertical line represents a reverse shock (Tsurutani *et al.* [6]) which marks the end of the interaction region between the high-speed stream and the background plasma. In this case the background plasma involves the presence of a magnetic sector (heliospheric current sheet) crossing which is characterized by the higher density interval during the first half of day 25. The interaction region itself is characterized by the gradual increase in the solar wind speed, temperature increase, magnetic-field intensity increase and in this case a highly fluctuating field. These large amplitude fluctuations may originate from the compression of the high-speed stream Alfvenic field at the interaction region giving rise to large and negative B_z values which were responsible for the moderate to intense magnetic storm (shown in the D_{st} panel).

The most dramatic geomagnetic response to the corotating streams, during solar minimum, as studied by Tsurutani *et al.* [6] are the HILDCAA events associated with LAIAWTs that are typically encountered within the body of the streams. The substorm activity is generally most intense near the peak speed of the stream where the Alfvén-wave amplitudes are greatest, and decreases with decreasing wave amplitudes anti stream speed. The 27-day recurring HILDCAA events can each last 10 days or more, and the presence of two events per solar rotation was the cause of the exceptionally high AE average for 1974. HILDCAA events often occur during the recovery phase of magnetic storms and the fresh (and sporadic injection) of substorm energy leads to unusually long storm recovery phases as noted in D_{st}.

In the far trailing edge of the corotating stream, the IMF amplitudes become low, and there is an absence of large amplitude Alfvén fluctuations. This is related to and causes geomagnetic quiet intervals.

3. Storm-substorm relationship

The HILDCAA events represent an interesting type of magnetospheric response to solar wind energization. The fluctuating B_z fields associated with LAIAWTS give rise to intense substorm activity. However, the relatively short duration of the negative B_z intervals does not seem to effectively energize the ring current, whose amplitude is measured by S_{st} and is used to define the level of the geomagnetic storm activity (Gonzalez *et al.* [7]). Fig. 4, taken from the review paper by Gonzalez et *al.* [7], shows a contrast between the HILDCAA activity and typical substorm and intense storm activities. Fairly intense substorm injections are known to occur at modest levels of the negative B_z field. However, to bring the ring current closer to the earth, B_z fields (and related magnetospheric convection electric fields) of larger intensity and duration are necessary. Therefore, one can say that an intense storm is accompanied by intense and frequent substorms but that intense substorms can also occur in the absence of an intense storm. This is confirmed by the HILDCAA substorms, which have a frequent and intense character hut do not involve the development of an intense storm due to the lack of sufficiently large and sustained convection electric field that are commonly observed during intense interplanetary events associated with transient solar features such as corona] mass ejections (CME).

4. Discussion

In spite. of the abundance of LAIAWT observations since the original works of Coleman [1] and of Belcher and Davis [2], very little is known about the origin of these waves. Most of the observational features seem to indicate that these waves are originated at the sun especially in open field regions such as coronal holes. However. how these waves propagate and interact within the interplanetary medium is still a problem of present study.

Recently, observations of LAIAWTs at high heliospheric latitudes performed by the Ulysses spacecraft (Tsurutani *et al.* [8]) have helped to clarify some important aspects of the evolution o] these Alfvenic fluctuations. These observations suggest that the LAIAWT can be highly nonlinear ($\Delta B/|B| \cong$ 1 to 2) and that they can be the source of frequent interplanetary discontinuities. Tsurutani *et al.* [9] showed that such discontinuities arc of the rotational type and that they result from phase steepening of the Alfv&r-waves. The Ulysses observations also showed that these LAIAWTs are present mainly within a high-speed stream. which in the Ulysses case covered a wide region originated in a large polar coronal hole at the **sun.**

Among the theoretical interpretations of the LAIAWT evolution within the interplanetary medium some concepts dealing with the non-purity of the waves as well as with their parametric anti more complex (turbulent) evolution have been presented (i.e. Barnes [9], Hada *et al.* [10], Marsch and Tu [11]). More recently, Oliveira [13] extended those studies to a temporal chaotic regime associated with the dynamics of Alfvenic dispersive waves under a modulational conservative regime.

Acknowledgments

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